Reviewer 2 (Dr. Charalampidou)

[...]A general observation relates to the clarity around the materials studied. It’s not always evident which results correspond to Ailsa Craig Common Green and which to Ailsa Craig Blue Hone. While this distinction is made in some sections of the manuscript, it’s missing in others, which makes interpretation more difficult. Additionally, it’s not consistently clear whether the two rock types exhibit similar or different mechanical behaviours across the various analyses - especially since different types of results are presented for each (with the exception of a couple of graphs).

- In the *Materials and Methods* section, we will insert several sentences beginning on ll. 79 of the preprint summarizing which rock types are used for which areas of the study (on-ice experiments, macroscopic damage characterization, and microscopic damage characterization). We will also describe the rocks from Trefor for context. This should help to specify which rocks are used in which aspects of the study. We will additionally include the rock types studied for each figure to reinforce this point.
- The modified paragraph on ll. 75–79 will read as: “We studied curling stones from both Ailsa Craig (Firth of Clyde, Scotland) and Trefor (Llŷn Peninsula, North Wales). Two types of rocks from Ailsa Craig are used in curling stones: Ailsa Craig Common Green, which is currently used for the striking bands of Olympic-standard curling stones; and Ailsa Craig Blue Hone, which was used as the striking band in older stones, but is currently inserted into the running bands of the stones (Leung and McDonald, 2022; see Fig. 1b for locations of the running band and striking band). Two types of rocks from Trefor are used in curling stones: Blue Trefor and Red Trefor, both of which are typically used for striking bands. In general, this study focuses on the rocks from Ailsa Craig, although we integrated several different rock types into the study: the on-ice experiments used Ailsa Craig Common Green; the macroscopic damage characterization predominantly used Ailsa Craig Blue Hone, with ancillary Ailsa Craig Common Green and Red Trefor samples; and the microfracture descriptions used only Ailsa Craig Blue Hone. The on-ice experiments were limited by the availability of actively used rocks at Curl Edinburgh. Different rock types were used in the macroscopic damage characterization to illustrate the full extent of damage in curling stones. Lastly, Ailsa Craig Blue Hone displayed the most developed crescent-shaped fractures and was thus the focus for the microstructural aspects of the study.”
- In a general sense, the specific rocks used in the on-ice experiments are less critical, as the goal of these experiments is to document the stresses and strains of the impacts. The contact mechanics calculations may vary based on the choice of Young’s modulus (here, we used experimental data for Ailsa Craig Common Green from Leung 2020), but the calculations are approximate and thus the substitution of a different Young’s modulus would not be expected to substantially change the outcome. For reference, the experimental Young’s modulus determined by Leung (2020) for Ailsa Craig Common Green is 39 GPa, Ailsa Craig Blue Hone 37 GPa, and Red Trefor 29 GPa (Blue Trefor was not measured due to issues encountered during the experimental process). With

regard to the Ailsa Craig suite, the Young’s moduli of the Ailsa Craig varieties are considered to be equivalent. For Red Trefor, substituting a Young’s modulus of 29 GPa for 39 GPa yields a mean stress of 500 MPa for the maximum-velocity scenario (cf. 680 MPa for 39 GPa). Although this value is somewhat lower, it still lies at the maximum end of the uniaxial compressive strength for the rocks. Note that this calculation is only meant to be conceptual, as different rock types may experience different degrees of compression and hence develop differing contact areas, and this is considered beyond the scope of the present contribution.

- The greatest limitation in interpretation comes from the use of different rocks in the macroscopic damage analysis (in particular, Figs. 8-9). It was unfortunately very challenging to obtain striking band samples of the same rock type with varying damage states, and we do not know for how long these stones were played. As such, we chose to limit discussion on comparing between the rock types and their mechanical behaviors, instead focusing on the distribution of crescent-shaped fractures among the sample suite. In the macroscopic damage analysis results, the rock types are clearly labelled on Figs. 8-9. We will additionally add a paragraph after l. 239 specifying the limitations of interpreting the effect that different mechanical behaviors may have on the development of crescent-shaped fractures: “As a note, our macroscale analysis of the morphology and distribution of crescent-shaped fractures in this section utilizes samples spanning several different rock types. Due to the lack of sample availability, it was not possible to compare the same rock type with different damage states. As such, we do not consider the effect that different mechanical properties may have on the development of crescent-shaped fractures.”
- To focus on how microfractures evolve, and to implicitly avoid issues with mixing and matching between different rock types, the microscale damage analysis uses only Ailsa Craig Blue Hone samples.
- In the *Conclusions*, we will also address the fact that the differences in mechanical behaviors of Ailsa Craig and Trefor suites remain important future topics regarding the damage evolution of curling stones: “[...] With respect to curling stones, four different varieties exist (Ailsa Craig Blue Hone, Ailsa Craig Common Green, Blue Trefor, and Red Trefor), but their mechanical behaviors were not differentiated in this contribution. As such, further work is warranted to differentiate the dynamic behaviors of different curling stone types in order to understand how mineralogy and grain-size distribution influence the mechanical properties of granitoids, as well as how this leads to the accumulation of damage during repeated dynamic loading and Hertzian loading (e.g., Leung, 2020; Leung and McDonald, 2022; Padture and Lawn, 1995).”

It would also be helpful to clarify how pristine rock samples are identified, which ones have experienced greater loading, and what information is available regarding samples/rocks that were previously used extensively (or used in varying numbers of games) prior to testing. I believe, including this context would strengthen the narrative and better support the findings.

- Pristine rock samples of Ailsa Craig Blue Hone were derived from natural samples (that had not been made into curling stones). In terms of the rocks used in the on-ice experiment, it is mentioned on l. 84–86 that the stones were used for less than one season. Unfortunately, in the case of the aged curling stones that were analyzed in the macroscopic and microscopic damage characterization sections, there is no information on the number of games that those rocks have been played in. We can only estimate the number of collisions over a lifespan of 10–15 years, which would be 29,000 on a conservative basis, or around 320 impacts per centimetre (please refer to Leung, 2025, https://doi.org/10.5194/egusphere-2025-3499-AC1, for calculations and assumptions).

That said, I find this to be a very compelling and valuable piece of work!

- Thank you – we greatly appreciate your constructive and encouraging feedback.

Some more precise comments follow:

1. *Is it rock physics or mostly rock mechanics for the title?*
    - We agree that rock mechanics (i.e., the study of the mechanical behavior of rocks under various stress conditions) is a more suitable phrase than rock physics (i.e., the study of the relationship between physical properties of rocks and their geophysical responses). This will be changed in the title and text.

2. Is there any difference between Ailsa Craig Common Green and Blue Home in terms of the structure, minerals, grain size etc.?
    - Ailsa Craig Common Green and Blue Hone are interpreted to represent the core and chill-margin facies (respectively) of the Ailsa Craig intrusion (Harrison et al., 1987). As such, the two rock types have essentially the same chemistry and mineralogy. Texturally, the two are quite different, with Ailsa Craig Common Green containing mm-sized spherical druses of quartz, whereas Ailsa Craig Blue Hone is more equigranular (with the exception of sparse alkali feldspar microphenocrysts, present in both). These aspects are detailed in Leung and McDonald (2022). The microfracture characterization focuses solely on Ailsa Craig Blue Hone, and comparisons of the mechanical properties of the different rock types is out of the scope of this contribution.

3. *Lines 118-119: Could you visualise by eyes the rock powder? What was the advantage using the high-speed camera instead, if the powder was retrieved post experiment? Which type of curling stone was used during these experiments (Common Green or Blue Hone)? Have you observed any differences in the quantity of powder generated and the microstructure (if you have tested both Common Green and Blue Hone)?*
    - The primary intention of the high-speed camera was to determine the contact time of the curling stone impacts. The visualization of the rock powder was a secondary (unintended) observation that led to the analysis of the rock powder by SEM methods. In the absence of the high-speed

camera, the rock powder would have likely been missed, as it was not visible in the GoPro footage.

- Only Ailsa Craig Common Green was used for the on-ice experiments, mainly due to the availability of curling stones at Curl Edinburgh. Ailsa Craig Blue Hone is no longer used in striking bands of contemporary stones (see Leung and McDonald 2022), so it is more difficult to test this question. Although the quantity of powder is a very intriguing question, it would be difficult to address, given the variable damage states of the stones and the exact collisional parameters (i.e., collisional velocity).

4. *Section 3.3: What about the Ailsa Crag Common Green stone? Why not used for thin sections? Is it Crag or Craig (see line 75)?*
    - Although thin sections were also prepared for Ailsa Craig Common Green samples, we ultimately chose to focus on the Ailsa Craig Blue Hone stones due to the greater availability for damaged samples. Thank you also for flagging the spelling errors. The correct spelling is Craig, and all incorrect instances of “Crag” have been corrected.

5. What about the rest 21 experiments? Is there any reason why were not analysed/presented herein?
    - Please refer to our response to Reviewer 1’s comments regarding l. 171 for a description of our reply and proposed changes (Leung, 2025, https://doi.org/10.5194/egusphere-2025-3499-AC1, p. 10).

6. *On-ice experiments: what about lower impact velocities (~0.5 ms/-1)? Do you have an example that can provide a narrative/argument like that of hight velocities?*
    - Curling stones will deviate laterally from their intended trajectories (“curling”). At low velocities (e.g., ~ 0.5 ms^{-1}), this deviation is more substantial and experimentally challenging to control. Unfortunately, none of the high-speed camera experiments at low impact velocities were usable (see Leung, 2025, https://doi.org/10.5194/egusphere-2025-3499-AC1, p. 10). Although these low-velocity impacts could be achieved by pushing the stones into each other (rather than delivering them from 38 m away, as a curler would typically do), the primary intent of the study was to study damage accumulation in curling stones as an end in itself. As such, we decided to deliver the stones as true to the sport as possible, so this was ultimately not conducted.

7. *How have you defined the impact velocity range (0.5-2.9 ms-1)? I mean why this range?*
    - It is described on ll. 91–94 of the preprint that the common velocities for curling stone impacts are typically measured by recording the time that the stones cross two lines (called the hog lines). From my (DDVL) experience as a competitive curling athlete, typical hog-to-hog times for takeout shots range between 12–6.5 s, corresponding to measured velocities between

0.5–2.9 ms^{-1}. In actuality, the velocity can be as low as 0 (as defined by two curling stones just in contact, as in Exp. 0.4) and higher than 2.9 ms^{-1}, although velocities higher than 2.9 ms^{-1} are not common.

8. *5: My understanding is that all these are different experiments. Which of the two materials were used herein (Common Green and Blue Hone)? Is there any info about the history of deformation, i.e., which cycle each of those images show?*
    - Fig. 5 corresponds to the on-ice experiments, all of which were conducted with Ailsa Craig Common Green striking bands. This detail will be added to the caption of Fig. 5 to improve the clarity of the figure. Each image shows a different impact velocity. As it is difficult to replicate an impact on exactly the same impact area, cyclic testing was beyond the scope of this study. Additionally, we will add a note describing which rock types are used for which analyses of the study (see comment on p. 1 regarding proposed modifications to ll. 75–79 of the preprint).

9. *6: Does the Common Green stone show similar type of fractures?*
    - Yes, Ailsa Craig Common Green can show similar types of fractures (see Fig. 10 in Leung and McDonald 2022), although anecdotally the fractures seem to penetrate less deep as compared to Ailsa Craig Blue Hone. It is uncertain (and unfortunately, beyond the scope of the present study) whether this anecdotal observation reflects a difference in mechanical behaviors between the two Ailsa Craig varieties or just represents an apparent effect due to the ages of the stones.

10. *Is Fig. 6 and 7 from the same sample?*
    - No, Fig. 6 and 7 are not from the same sample, although they display similar crescent-shaped fractures. This is noted by the different sample numbers in the respective figure captions.

11. 8: How the grey and colour lines correlate – i.e. which data set is the coloured one if the whole dataset is in grey colours? What does 'n' stand for? 8e: what do the small circles represent? Which is the damage state – graph showing theta?
    - It is noted in the figure caption that the grey dataset represents the whole dataset. "n" stands for the number of observed fractures, and the small circles represent outliers; these will be included in the figure caption for Fig. 8 (thank you for suggesting this addition). To improve the readability of the graphs in subfigure (e), we will modify the figure caption to specify the graph for r (left graph) and theta (right graph).

12. *Line 218: pls erase second have.*
    - Thank you for flagging this typographical error – it has been corrected.

13. *9: What does the length (i.e., 30 cm) stand for? How do you define maturity? What does 'n' stand for?*
    - The length (30 cm) is a scale bar.

- Maturity is defined on ll. 219–222 based on the observed development and depth of exhumation of the crescent-shaped fractures.
- “n” stands for the number of total observed fractures and will be added to the figure caption.

14. *10: How do you know that some of these fractures were not pre-existing (existing before the experiment), or else pre-existing fractures have not further propagated? Which of the two Ailsa Craig rocks is the one in Fig. 10?*
    - Curling stones are manufactured such that large-scale fractures are rejected. Some of the smaller-scale fractures could certainly be pre-existing fractures. Figs. 11 and 12 better explore the possibility of pre-existing fractures.
    - To improve the clarity of the text, we will add to the caption for Fig. 10 that this sample corresponds to Ailsa Craig Blue Hone.

15. *Lines 271: how do you identify pristine and juvenile stages?*
    - Maturity is defined on ll. 219–222 based on the observed development and depth of exhumation of the crescent-shaped fractures. Pristine is not explicitly defined in this section, and as such we will include a definition of pristine following its first mention on l. 150. The pristine samples used here are natural samples that were not manufactured into curling stones. The incipient damage state refers to “partially formed fractures, which may be formed in segments”, whereas juvenile refers to “fully linked crescent-shaped fractures, with 3D fracture surface hidden”.

16. *Line 381: why rock physics and not rock mechanics?*
    - This has been modified according to our response to item 1 of this review.

17. *Line 385: The damage evolution of curling stones consists of several damage states: pristine, weakly incipient, incipient, juvenile, and mature. How are those stages defined? If the same curling stone was used for previous games, how do you define the pristine sample? – I think I’m missing something here.*
    - Maturity is defined on ll. 219–222 based on the observed development and depth of exhumation of the crescent-shaped fractures (see also reply to comment 15).
    - With respect to the conceptual damage evolution model, the “pristine” damage state refers to a more broad state where no macrofractures are observed, representing somewhere between a new stone and a stone that has begun to develop weakly incipient crescent-shaped fractures. There is, of course, expected to be some degree of damage (i.e., flattening of the striking band and ejection of rock powder, as well as pitting), but there is otherwise no visible macroscopic evidence of fracturing.

18. *Lines 385-410: it would be great to support this narrative with images you have presented before in the results (or the accompanied material).*

- Although Fig. 15 is conceptual, the illustrations are based on actual profiles of rocks analyzed in this study. We feel that the addition of extra images would confuse readers rather than enhancing the figure. As such, we have decided not to adopt this suggestion, although we appreciate the rationale behind it.
- To facilitate the transition to the conceptual model for damage evolution, we will incorporate our reply to Reviewer 1 (Leung, 2025, https://doi.org/10.5194/egusphere-2025-3499-AC1, pp. 2–4) regarding cyclic Hertzian damage experiments on silicon carbide by Padture and Lawn (1995) which complement our results.

19. *I can see a damage evolution – can you please elaborate more on the actual model? I would possibly name it conceptual model.*
    - We have renamed the subsection to read “Conceptual model for damage evolution in curling stones”.

20. *Conclusions- they need a bit of extra work and some narrative instead only bullet points.*
    - We will reformat the conclusions to read as a narrative. Additionally, we will include the limitations of the manuscript to highlight potential areas for future work. Please refer to Leung (2025, https://doi.org/10.5194/egusphere-2025-3499-AC1, p. 1) and pp. 1–2 of this response for the proposed additions regarding the limitations of the manuscript.
    - The modified conclusions section will now read as: “In this contribution, we have shown that curling stones are momentarily stressed to at least 300–680 MPa for high-velocity impacts (2.93 ± 0.15 ms^{-1}), exceeding the threshold for fatigue damage during dynamic loading. The impacts are shown to be dynamic in nature, as evidenced by (1) high strain rates (24 ± 4 s^{-1}) that approach those of co-seismic rock pulverization; (2) the ejection of rock powder as observed by the on-ice experiments; and (3) the presence of striations on crescent-shaped fractures that are interpreted to have formed by dynamic microfracture propagation (mirror-mist-hackle pattern). Crescent-shaped fractures are interpreted to be Hertzian cone fractures on the basis of their relationship to contacts between colliding curling stones, as well as their conoid morphology that is reminiscent of Hertzian cone fractures observed in other natural and engineered materials. We interpret crescent-shaped fractures to develop early via high-velocity impacts, in which damage initiates mainly as intragranular microcracks in feldspars, which propagate into transgranular microcracks that eventually develop into through-going microfaults as crescent-shaped fractures. Subsequent impacts propagate and coarsen these crescent-shaped fractures, and a localized damage zone develops in the collet between the crescent-shaped fractures and the striking band.”

All the best,

Elma Charalampidou

Thank you again for your time and for your constructive feedback, which will serve to strengthen the manuscript.

References cited in this reply:

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